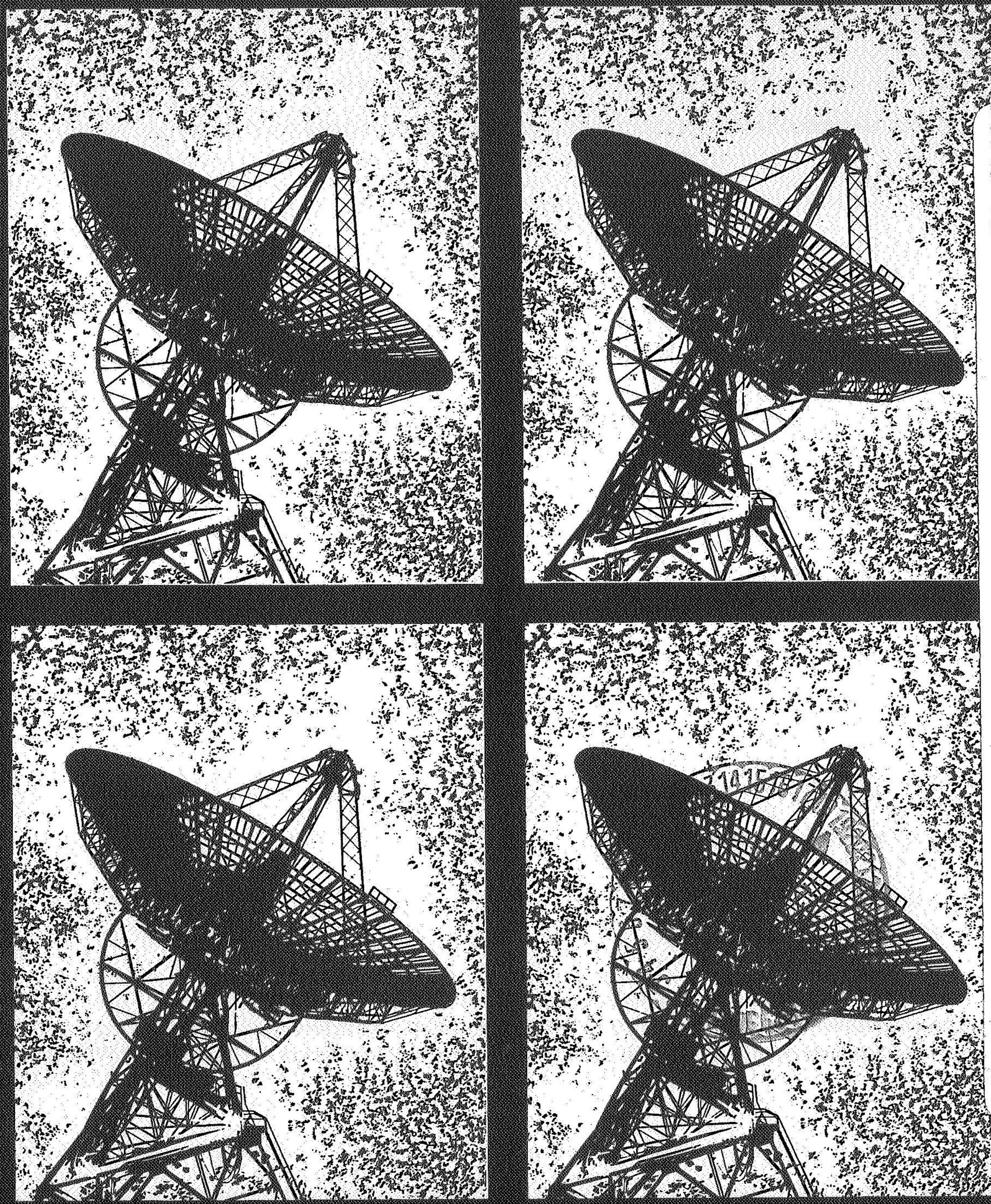
America In Space | The First Decade

NASA-EP-55

SPACECRAFT TRACKING



National Aeronautics and Space Administration

America In Space: The First Decade

This is one of a series of booklets published on the occasion of the 10th Anniversary of the National Aeronautics and Space Administration.
These publications are not intended to be comprehensive history, nor do they deal with all the facets of NASA's aeronautical and space activities. Rather they are overviews of some important activities, programs and events written for the layman in terms of the several science disciplines.

Each of these subjects is treated in more depth in other NASA publications and in scientific journals.

October 1, 1968

Titles in this series include:

EP-51 Space Physics and Astronomy
EP-52 Exploring the Moon and Planets
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SPACECRAFT TRACKING

by William R. Corliss

National Aeronautics and Space Administration, Washington, D.C. 20546

Introduction

Spacecraft tracking involves much more than merely finding and following each spacecraft as it traces its own unique course through space. The location of the spacecraft must be accurately determined so that the scientific data it is acquiring can be matched to that position. Also, the spacecraft's path is precisely monitored because small perturbations yield valuable information about changes in the gravity field, variations in atmospheric density, to name but two.

"Spacecraft Tracking" deals with this precise locating of spacecraft dispatched from Earth. Tracking is difficult to separate from spacecraft communications in the sense that NASA's three worldwide ground-based networks perform both functions. Most NASA network stations possess antennas that can both track and acquire spacecraft data. Despite this dual capability of NASA hardware, spacecraft communications—a subject dealing with the transfer of information to and from spacecraft and the Earth—has a different theoretical background. Because of this distinction, spacecraft communications is treated in another booklet in this series: "Linking Man and Spacecraft."

Gerald M. Truszynski
Associate Administrator for
Tracking and Data Acquisition

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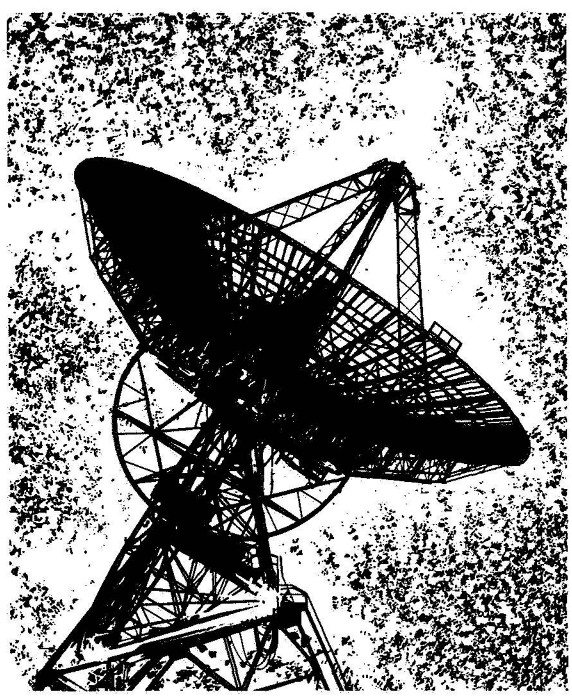
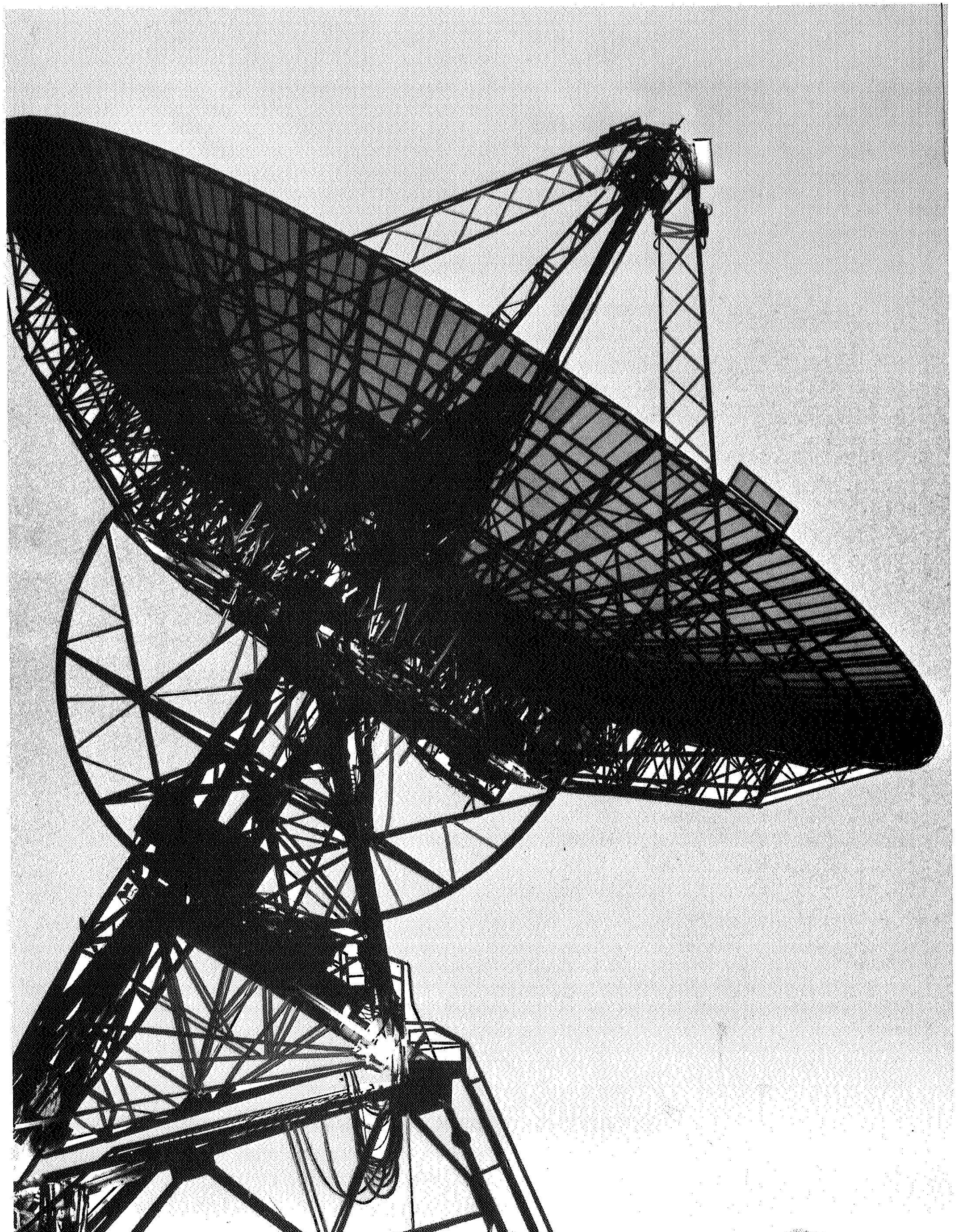




Spacecraft Tracking

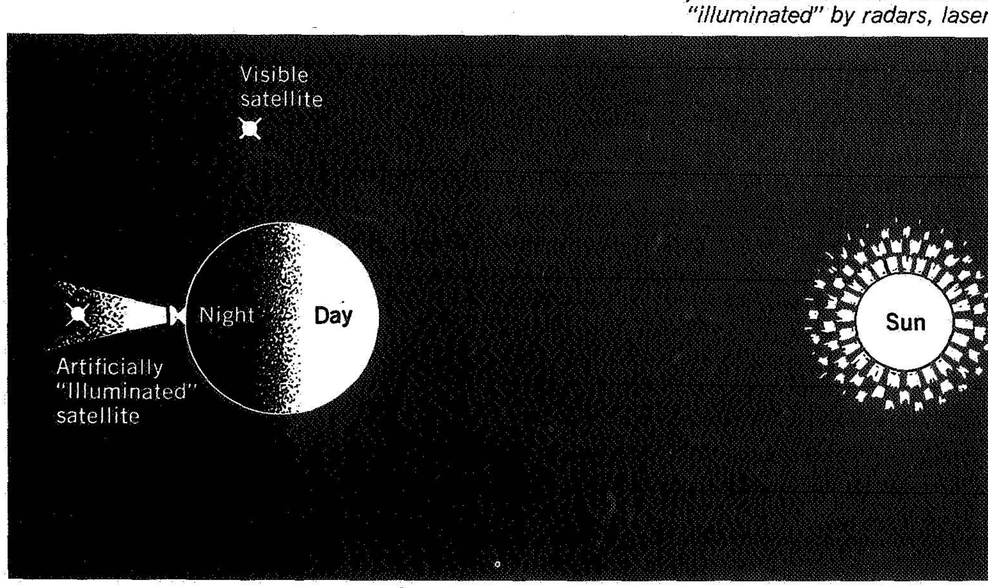
The Celestial Haystack

Finding and following spacecraft as they crisscross the sky overhead is called tracking. In 1958, when the number of satellites in orbit could be counted on the fingers of one hand, the major tracking problem was finding the tiny satellites in the immensity of space. Between 1958 and 1968, however, almost 800 artificial satellites and space probes were launched. Today's tracking problem is not finding spacecraft, rather it is sorting them out and coping with the heavy traffic flow. Even more traffic is caused by the growing stream of space debris—pieces of defunct rockets, exploded spacecraft, the flotsam and jetsam of space exploration. Well over 1000 pieces of space hardware are in orbit at any one moment. Tracking spacecraft is akin to keeping tabs on all the aircraft around a busy airport, except that the targets are much higher and travel much faster.

Remember those exciting days when the first satellites were being shot into orbit? In the early evening, people would rush outdoors to see the bigger ones—still illuminated by the Sun below the horizon—cruise across the background of the stars. Many satellites are still tracked by reflected sunlight, but only when the Sun and satellite are in the right positions. When we wish to track spacecraft 24 hours a day we must make them visible artificially. We cannot duplicate the Sun but we can shine radar, laser, and/or radio beams on them and detect the echoes and reflections.

The easy way to track spacecraft, though, is to make them announce their presence themselves with a beacon or transponder. The great majority of satellites and space probes carry radio transmitters that continuously signal their locations to tracking antennas on the ground; these are called beacons. Other spacecraft, such as Gemini, include transponders in their payloads. A transponder is a beacon that sends out a signal when it is triggered by a radio or radar signal from Earth.

1 *Satellites are best seen visually just after sunset and just before sunrise. Satellites can also be artificially "illuminated" by radars, lasers, and radio transmitters.*



Beacons and transponders eventually fail and their signals fade away. The spacecraft then becomes "dark" or "inactive" and must be illuminated by the Sun or a powerful Earth-based radio transmitter if it is to be tracked.

Consider the different kinds of spacecraft and how their various flight regimes affect the way we track them. The flights of sounding rockets are short in terms of time and distance. They can be tracked easily by radars and telescopes located right at the launch site.

Satellites present a more difficult problem. As their launch rockets rise from the pad, gain altitude, and arch over toward the southeast out over the Atlantic (assuming a Cape Kennedy launch) they are followed by launch site radars and optical instruments. Jettisoning lower stages and ascending rapidly, the rocket is passed from tracking station to tracking station along the chain of islands and ships stretching to Ascension Island in the South Atlantic. As the spacecraft approaches Africa it should be in orbit. If the African tracking stations know where to look they can pick up (acquire) the satellite, track it, and pass it on to the next station. The point here is that satellite tracking requires stations around the world—in other words, a network of stations rather than a few instruments at the launch site.

Tracking lunar, deep space, and interplanetary probes is still more difficult. Not only do we need a worldwide network to watch them, but we must maintain contact with them when they are hundreds of thousands, even hundreds of millions of miles away. Such distances are far beyond the capabilities of the radars and optical tracking equipment so useful for following satellites. A special radio tracking scheme is needed.

Each type of spacecraft thus has its own set of requirements:

Sounding rockets—Launch site radars and optical tracking equipment.

Satellites—Worldwide networks of radio, radar, and optical tracking stations.

Space probes—Worldwide networks of long distance radio tracking stations.

The subject of spacecraft tracking is really twofold: (1) what are the technical methods for finding and pinpointing spacecraft; and (2) how can these techniques be organized into worldwide networks that can keep track of the hundreds of machines we have put into orbit.

Ranges And Networks

To keep tabs on its many spacecraft, NASA operates three global networks and sponsors the operation of a fourth:

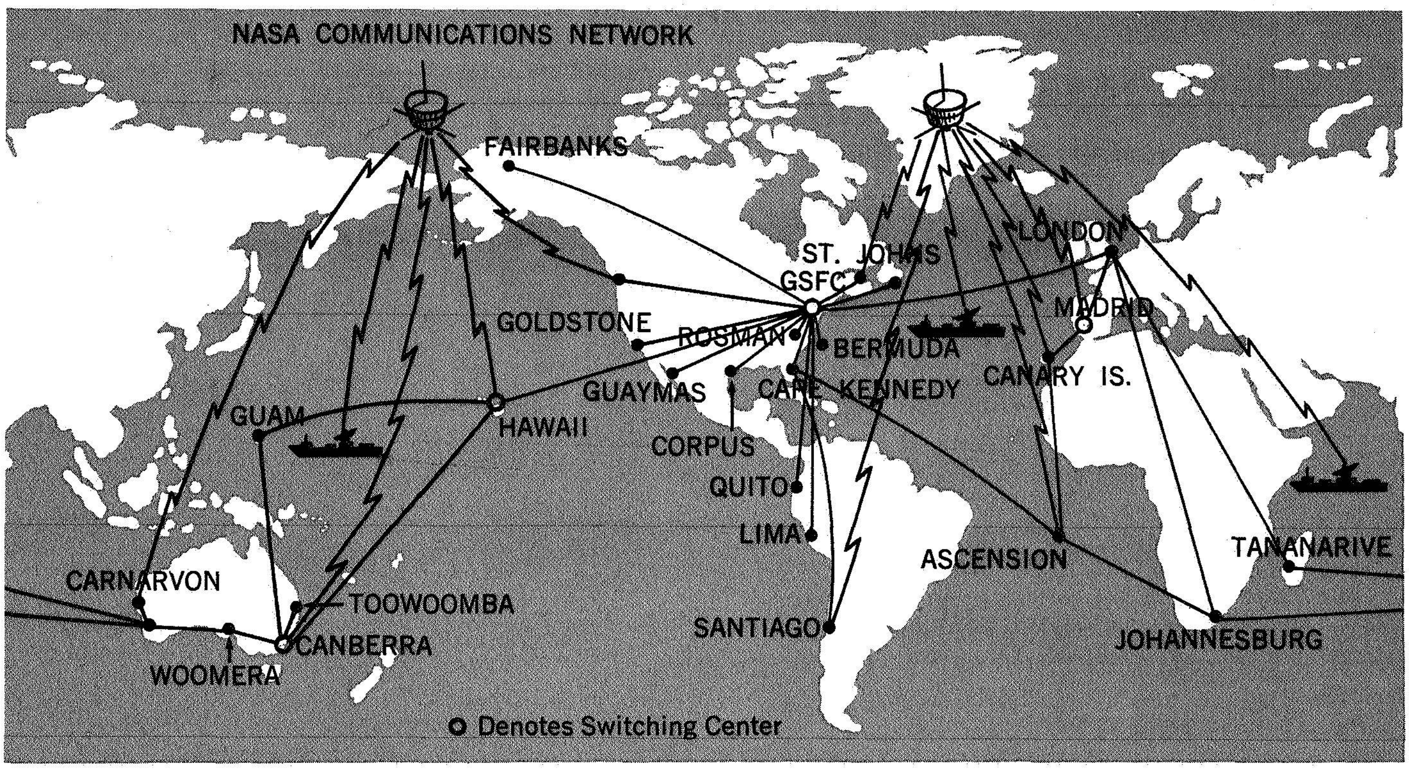
STADAN	Space Tracking and Data Acquisition Network	For tracking unmanned scientific and applications satellites
SAO	Smithsonian Astrophysical Observatory optical network	For precision tracking of satellites
MSFN	Manned Space Flight Network	For tracking manned satellites and lunar spacecraft
DSN	Deep Space Network	For tracking lunar, planetary, and deep space probes

Each of NASA's networks has a different mission that cannot be carried out well by any of the others. As the evolution of each network is described, it will be seen that the tracking techniques are fundamentally different for each. There is, however, considerable interchange of tracking data and continual mutual support among NASA's networks. This is also true for the worldwide networks maintained by the U.S. Air Force and Navy for tracking their military satellites.

A random sprinkling of tracking stations around the world does not make a network. The stations must be located where they will do the most good for the least cost. To illustrate, there are no tracking stations in Antarctica because it would be very expensive to maintain a station in that climate. NASA tracks its polar satellites from a station outside Fairbanks, Alaska. Most tracking stations, however, are concentrated within a wide equatorial belt 40° north and 40° south of the equator. The great bulk of U.S. spacecraft pass over this belt.

Tracking networks need good ties with the rest of the world, especially with the network control center, where

2 *Map of major NASCOM communications lines. NASCOM provides worldwide real time communications between NASA tracking stations.*



all tracking and telemetry data converge for analysis. Three strong factors bind network stations together: (1) a high-speed, high-capacity communication system; (2) an accurate timing system; and (3) an accurate, common geodetic framework. The need for the second and third are obvious; we must know precisely where the stations are located (the geodetic factor) and we must have confidence that their clocks are synchronized; otherwise, tracking measurements will be worthless.

NASA ties its four networks together with a common communication system called NASCOM. Using submarine cables, land lines, microwave links, and communication satellites, NASCOM operates in what astronautical engineers call real time. This means that commands, data, and voice messages are transmitted anywhere on Earth in only a fraction of a second. NASCOM employs hundreds of thousands of miles of communication circuits plus a main switching center at Goddard Space Flight Center, Greenbelt, Maryland, and subsidiary switching centers overseas. NASCOM is not only vital to the tracking and control of spacecraft but it is a valuable national resource as well.

Before describing NASA's big networks, tracking ranges should be discussed. A range is a localized version of a network. For sounding rockets, a single tracking station with a variety of instruments suffices.

For missile and high altitude aircraft tests, a chain of interconnected stations is employed. A range is linear and of limited length, not two-dimensional and worldwide like a network. Nevertheless, its stations must be tied together in the same ways network stations are unified, and the tracking equipment is similar.

The biggest U.S. ranges extend outward from Cape Kennedy, Florida, and Vandenberg Air Force Base, California. The Eastern Test Range (ETR) begins at Cape Kennedy and runs southeastward along a string of islands and ships for some 5000 miles. NASA operates facilities at some points along the ETR. On the West Coast, Vandenberg is the hub of four separate ranges collectively called the Western Test Range (WTR). NASA launches most of its polar satellites from here. In between Cape Kennedy and Vandenberg, the U.S. operates ten smaller ranges.

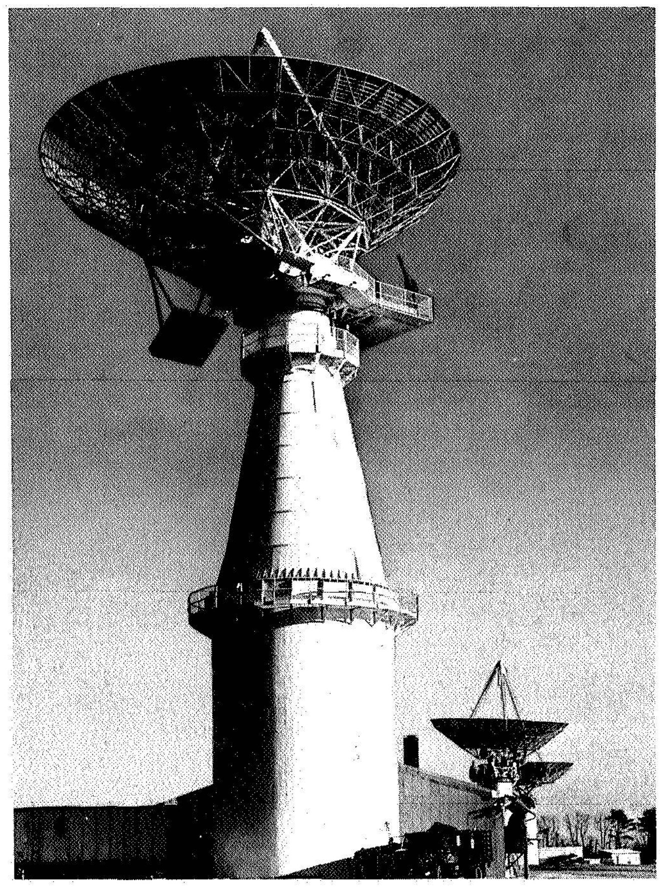
NASA operates two of these smaller ranges: Wallops Island, on the Virginia coast; and the X-15 High Range, at Edwards Air Force Base, in the California desert.

From Wallops NASA launches many upper-atmosphere chemical-cloud experiments that are seen for hundreds of miles. A few small satellites, such as Explorer XVI, have been launched from Wallops on the Scout rocket. Several varieties of radars line the beach at Wallops, tracking sounding rockets, small satellites and pilotless aircraft launched from the several pads at Wallops. The Spandar radar with its 60-foot paraboloidal reflector is particularly impressive. It can track spacecraft 5000 miles away. A large number of tracking telescopes and cameras complement the radars. Wallops also employs an instrumented ship, the Range Recoverer, as a downrange station.

STADAN

STADAN, NASA's Space Tracking and Data Acquisition Network, grew around the basic core of eleven Minitrack tracking stations set up by the U.S. Naval Research Laboratory for the Vanguard Program in 1956 and 1957. In the early days of the space effort, Minitrack was the bulwark of U.S. tracking operations. Its radio interferometers still track most of NASA's scientific satellites and any other spacecraft carrying 136 MHz* radio beacons.

** 1 MHz = 1 megahertz = 1 megacycle per second = 1,000,000 cycles per second.*



3 *The Spandar radar antenna at Wallops Island. Other radars are shown in the background.*

The Minitrack Electronic Fence

Suppose you shoot a volleyball-sized sphere into orbit from Cape Kennedy; you then turn and face west and wonder when, where, and even *if* that tiny sphere is going to come in over the horizon at 16,000 miles per hour. It would be almost impossible to find it with narrow-angle tracking telescopes and thin, pencil-like radar beams. To be certain of finding their satellites Vanguard engineers built an electronic fence that the spacecraft would have to cross if they were in orbit. This fence formed the basis of the Minitrack Network. The name Minitrack comes from minimum weight tracking; the weight being that of the tiny radio transmitter aboard the miniaturized Vanguard satellite. Having a voice of its own, a Vanguard satellite announced itself to the north-south fence of radio listening posts along the 75th meridian from Washington, D. C., deep into South America. The fan-shaped receiving patterns of the north-south Minitrack stations overlapped so that passing satellites had to cross the fence.

4

By crossing the Minitrack fence, a satellite merely announced that it was there—hardly the accurate tracking data the Vanguard engineers wanted. A scheme was found that utilized the radio waves from the satellite transmitter to fix the satellite position. The basic idea came from the science of optics. It was called interferometry; and it had been employed for decades to measure angles and distances with fantastic accuracy. In radio interferometry, the idea is scaled up from the wavelengths of light (5×10^{-5} cm) to radio wavelengths (about 300 cm for Minitrack).

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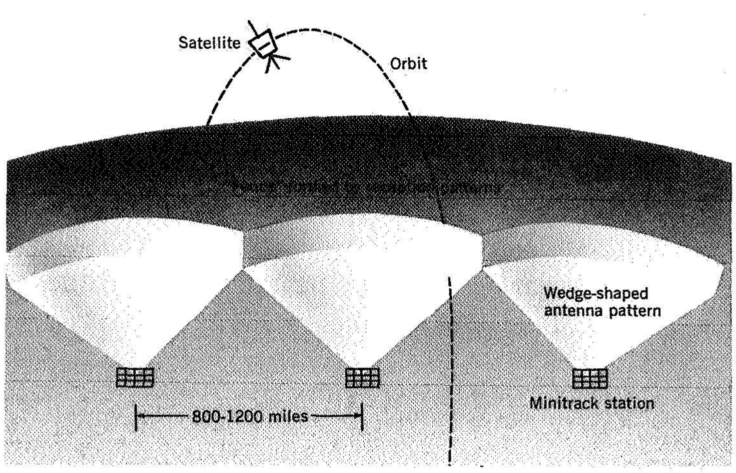


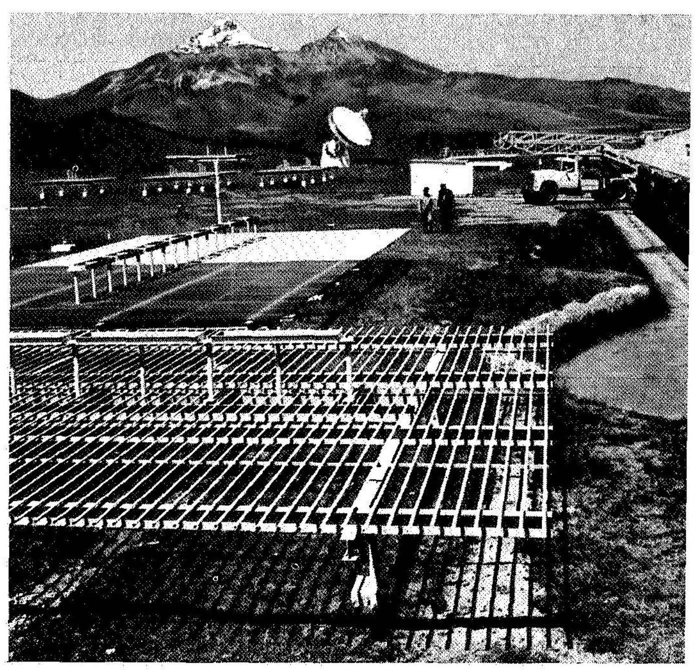
4 *Optical tracker at Wallops Station.*

5 *The early Minitrack stations along the 75th meridian formed an electronic "fence" that satellites had to cross.*

6 *The Minitrack array at Quito.*

Consequently the instrument itself grows from table-top size to football-field size.

A radio interferometer determines the direction of the signal source very accurately. If we set up a line of equally spaced radio receiving antennas, say, north-south along our football field, they will not in general receive the crest of each satellite-sent radio wave at the same instant. If the satellite flies north of the station, the northernmost antenna will be the first to pick up the crest of the wavefront; the southernmost will be the last. Only if the satellite is plying a perfect east-west course bisecting the station's antenna array will all antennas receive the wavefront at the same instant.

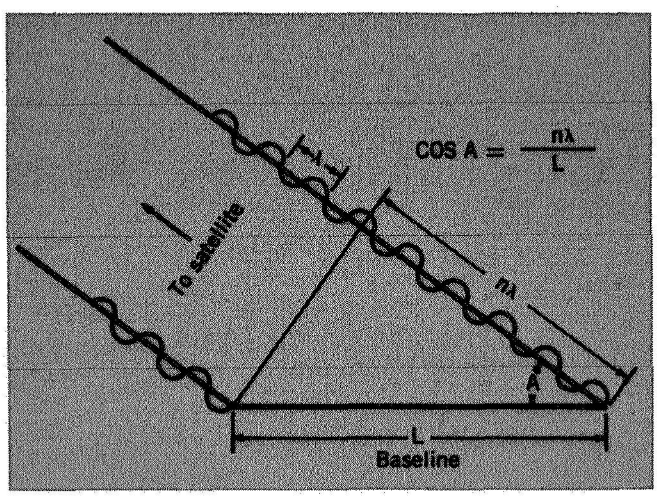


6

A Minitrack interferometer measures the angle the satellite-transmitted wavefront makes with the north-south line of antennas. It does this by counting the number of wavefronts that pass before adjacent antennas receive the same wavefront. (See diagram.) Angular precision comes from installing many separate receiver antennas in a line at each station. By using long antenna baselines at each station and then combining tracking data from several stations, the Minitrack system can measure the angular position of a satellite to within 20 minutes of arc.

A north-south line of receiving antennas in itself is insufficient because only one satellite angle can be computed. To measure the second angle, Minitrack stations also have an east-west line of antennas. The complete Minitrack antenna array forms a cross at each station. Along the 75th meridian, the north-south antenna patterns of the stations combined to create the original Minitrack fence.

Unlike radar and other tracking schemes, Minitrack radio interferometry does not provide target range and velocity; only target direction. Angular data alone, however, are sufficient to establish a satellite's orbit.



7 An interferometer measures the angle of a transmitting satellite by the phase difference between the radio waves received at different receiving antennas in a linear ground array.

The Minitrack network went into operation in October 1957, just after Sputnik 1 was launched. It proved highly successful in tracking the early U.S. Vanguard and Explorer satellites. In October 1958, newly created NASA absorbed Project Vanguard and, along with it, the operating responsibility for the Minitrack network. As NASA laid out its plans for space exploration, it became apparent that some Earth satellites, and lunar probes especially, could not be tracked accurately by radio interferometers.

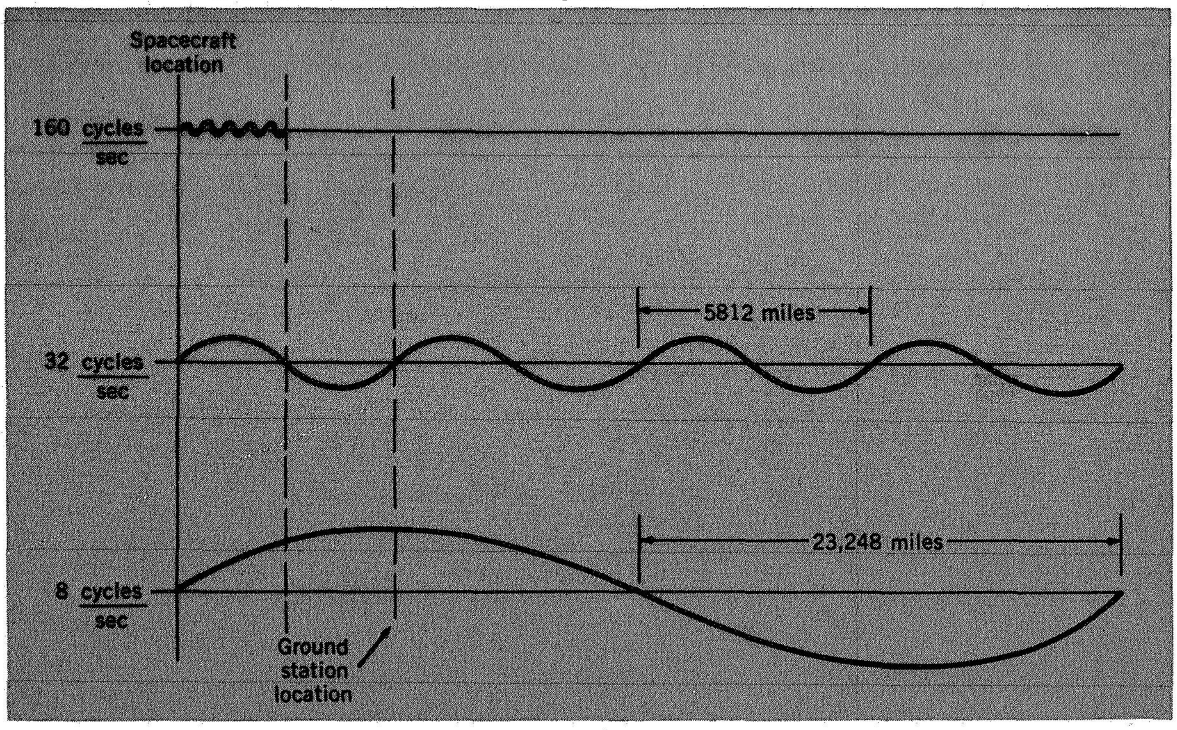
Sidetone Tracking

Suppose that NASA has just launched a spacecraft toward the Moon. Minitrack stations can measure its angular bearing as it heads toward the Moon; but is that sufficient? As the probe leaves the Earth behind, its angular bearing becomes less and less important because its motion is almost entirely directly away from Earth. The probe may travel 10,000 miles with hardly a change in its angular bearing. The same sort of difficulty arises with Earth satellites in highly elliptical orbits. Here, angular bearing remains almost unchanged when the satellite is traveling slowest near apogee. Minitrack angle tracking had to be supplemented with range and range rate (velocity) tracking.

NASA's Goddard Space Flight Center developed a tracking system based on the "range and range rate" technique, without the use of radar. The satellite or probe carries a special transponder that is triggered by a signal from an Earth-based tracking station. In response, the transponder emits a radio signal (called the carrier) that is modulated by eight mathematically related signals called sidetones. The transponder carrier signal is at 1705 MHz, but it is varied* at 8, 32, 160, 800, 4000, 20,000, 100,000 and 500,000 cycles per second. Except for the 8 at the beginning of the series, the sidetones form a geometric progression. Each of the sidetones may be thought of as a ruler. The 100,000-cycle/sec ruler is 1.86 miles long—the distance from crest to crest of the radio waves. The 20,000-cycle/sec sidetone ruler is five times longer, or about 9.3 miles. At 32-cycles/sec, the measuring stick is about 5812 miles long.

**Actually the carrier's phase is varied, but this subject is beyond the scope of this booklet.*

8 The Goddard range and range rate system may be conceived in terms of radio wavelengths as measuring sticks.



When the satellite transponder replies to the signal from Earth, it constructs (by radio) eight separate, parallel lines of rulers between itself and the Earth station. If the spacecraft is 5812 miles away, there will be exactly one 32-cycle/sec between spacecraft and Earth. How does the tracking station know that it is not really looking at the end of the second 32-cycle/sec ruler and that the spacecraft is really 11,624 miles away? This ambiguity, as tracking engineers call it, can be resolved by looking at the much longer 8-cycle/sec sidetone. The relationship between the two sidetones will be quite different if there are two 32-cycle/sec rulers rather than one. In a similar fashion, the station's electronic circuitry can distinguish between other arrangements of rulers.

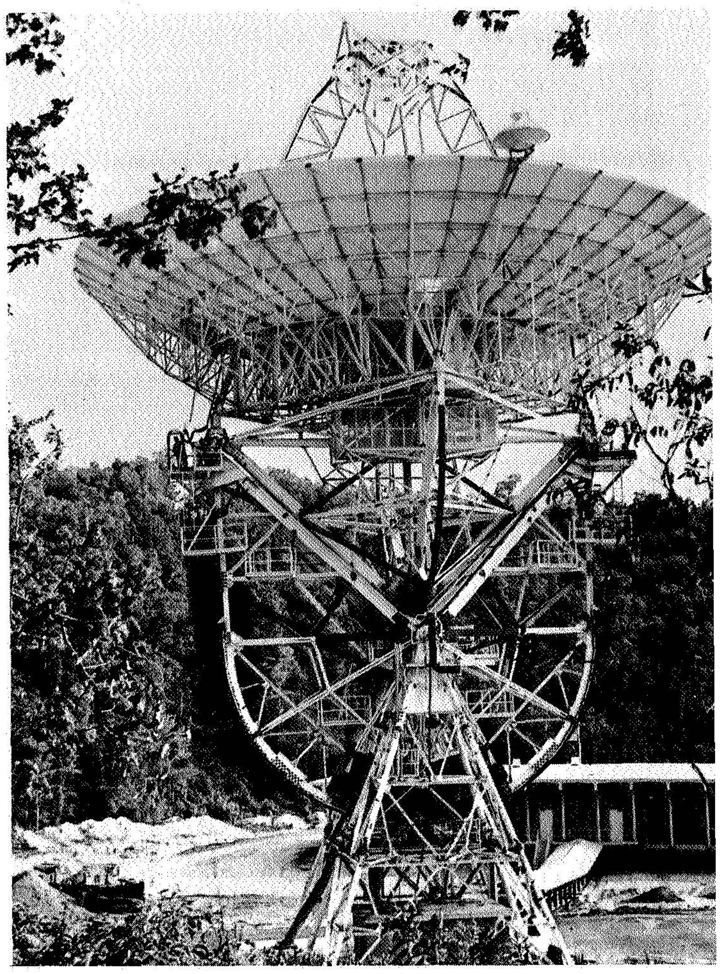
The smallest sidetone ruler (the 500,000-cycle/sec one) is only about a third of a mile long. By comparing the wave shapes of the high frequency sidetones, a NASA tracking station can compute spacecraft range to within 45 feet, even if the spacecraft is as far away as the Moon. Range rate (spacecraft velocity toward or away from the station) can be found by measuring the Doppler effect; that is, the amount the transponder wavelengths are compressed or stretched by the motion of the spacecraft.* Range rate can be measured to within 4 inches per second for a spacecraft at lunar distances.

The introduction of range and range rate equipment at certain Minitrack stations was one of the changes that caused the metamorphosis of Minitrack into STADAN. Two other major changes were:

1. A general rearrangement and consolidation of stations. Rearrangement occurred when NASA no longer needed all the stations in the electronic fence along the 75th meridian because better tracking at the launch ranges provided good orbital data a few minutes after liftoff. Instead, NASA needed high latitude stations to track polar satellites, such as the Polar Orbiting Geophysical Observatories and the Nimbus weather satellites.
2. The addition of large 40-foot and 85-foot-diameter steerable paraboloidal dishes at several stations to permit faster collection of data from

**The common analogy refers to the rise and fall of the pitch of a train whistle as it approaches and recedes from the listener.*

big NASA satellites, such as the Orbiting Geophysical Observatories and Nimbus satellites. These big dishes are usually *not* used for satellite tracking.

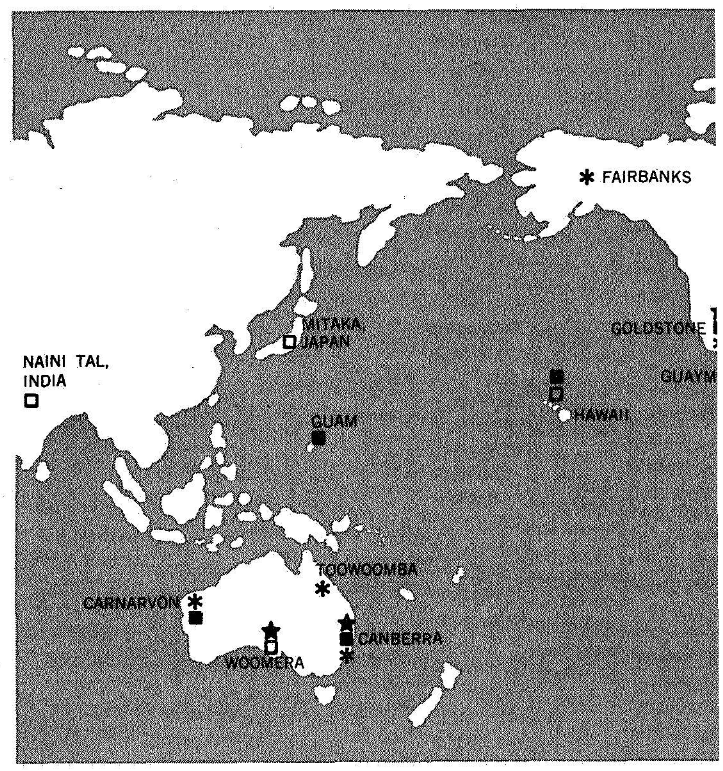


STADAN today, when compared with its progenitor Minitrack, consists of fewer, better equipped, and more widely distributed stations. Actually, the most important function of STADAN is now data acquisition rather than tracking. The hub of STADAN is at Goddard Space Flight Center, where all NASCOM communication lines converge. Scientific and applications satellites are controlled from Goddard by commands dispatched from Goddard via NASCOM to the STADAN station working the satellite of interest. The STADAN station relays the command to the satellite on the uplink portion of the radio link and receives data on the downlink portion. In essence, STADAN plus satellite form a huge, electrically connected machine run by mission controllers at Goddard.

The Smithsonian Optical Network

The Smithsonian Optical Network evolved concurrently with the Minitrack network in 1956 and 1957. In those days, no one knew for sure that radio interferometry would work well in tracking satellites. For this reason, the United States developed two separate systems based on different principles.

The Sun is obviously the best satellite illuminator of all. Unfortunately, most satellites are so small that they can be seen only with good telescopes. And just where does one point the telescope? The sky is a big place to search at random for a pinpoint of light moving slowly across the celestial sphere. Furthermore, satellites are not illuminated by the Sun at all when they are in the Earth's shadow; and in the daytime the poor contrast between satellite and bright sky makes seeing poor. The best time to see a satellite by sunlight is just before dawn and just after sunset, when the satellite is lit but the Earth below is not.

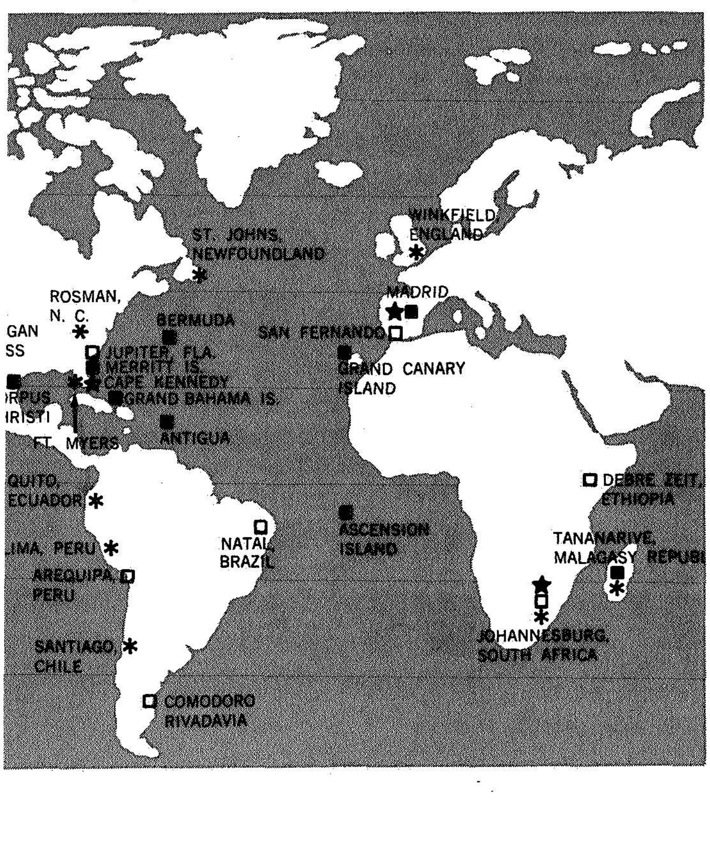


9 *One of the two 85-foot telemetry receiving antennas at the Rosman, N.C., STADAN station.*

The Smithsonian Astrophysical Observatory (SAO), set up an effective plan for optically finding and then precisely tracking the country's first artificial satellites.

The optical location of a satellite is simple in principle: organize lots of people the world over to watch the dawn and twilight skies. This was the core of the SAO Moonwatch Project. Through the astronomical fraternity and the great enthusiam for space in 1957, the SAO was able to establish almost 200 teams of amateurs in this country and abroad. Moonwatch teams were armed with low power telescopes. Several team members would arrange their telescopes north-south along the local meridian, creating in effect an optical fence analogous to the Minitrack radio fence. With Moonwatch teams on the lookout all over the world, someone would see a new satellite eventually. When a team spotted a satellite-like object, it immediately telegraphed the object's time of passage over the local meridian to SAO Headquarters in Cambridge, Massachusetts. With enough telegrams in hand, the SAO computer could calculate a crude orbit.

But a crude orbit is of little value to scientists who want to analyze slight orbital changes (perturbations) caused by the Earth's bulge and the pressure of sunlight. in the SAO scheme, Moonwatch was only the satellite finder. For precision tracking of satellites once they were located approximately, the SAO built a special camera that photographed them against the background of the fixed stars. Since the positions of the brighter stars are known with great precision, the satellite's



10 *Locations of major NASA Tracking Facilities.*

■ MANNED SPACE FLIGHT NETWORK

✱ SPACE TRACKING AND DATA ACQUISITION NETWORK

★ DEEP SPACE INSTRUMENTATION FACILITIES

□ OPTICAL TRACKING NETWORK

11 *The Baker-Nunn tracking camera.*

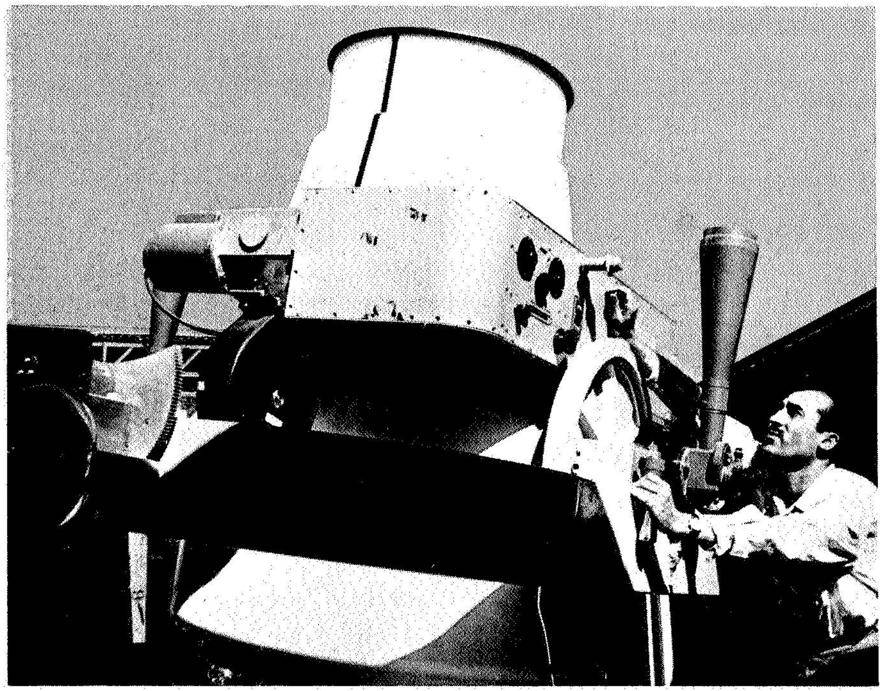


image* on the photographic plate would also be known very accurately.

The special, wide aperture camera, known as the Baker-Nunn camera, was the most important piece of hardware in the SAO optical tracking program. With a 30° field of view it can photograph a satellite too faint to be seen with the naked eye. By careful measurement of the images on Baker-Nunn plates, the angular position of a satellite can be found to within two seconds of arc (compared with 20 minutes for Minitrack).

The SAO installed Baker-Nunns at 12 stations around the world, generally within a belt 30° above and below the equator. The primary task of the big cameras has been high precision optical tracking of satellites for geodetic and geophysical studies. Although the Baker-Nunns provide more accurate tracking data than the Minitrack interferometers, analysis of the plates is lengthy and laborious. Minitrack and the SAO optical network turned out to be complementary. The former is good for locating satellites and providing approximate orbits; the latter is more precise once the satellite's rough location is known.

**A satellite's image is actually a short streak because a satellite moves across the sky much faster than the more distant fixed stars.*

The success of Minitrack in finding satellites led to the disbanding of the Moonwatch teams in the early 1960s. The SAO network, which is run by SAO for NASA, has changed little since 1958. Its 12 cameras have materially advanced the science of geophysics with a minimum investment of money.

The Manned Space Flight Network (MSFN)

The purpose of NASA's Manned Space Flight Network is to track and communicate with manned spacecraft in Earth orbit or on a voyage to the Moon and back. Satellites are satellites; why not use STADAN for tracking manned satellites rather than build a whole new network? It is the payload—the astronaut—that makes the difference. We could allow an unmanned satellite to splash into the Atlantic and sink, but not an astronaut.

Suppose a manned satellite is launched from Cape Kennedy out over the Atlantic. Within a few minutes it has pitched over and is headed downrange toward Africa with a speed approaching 15,000 miles per hour. But is it in a safe orbit? Its velocity could be just short of that needed for orbit so that it might impact on the African land mass. For the safety of the astronauts, we must know if the desired orbit has been attained *before* the point has been reached at which the spacecraft's path would cause it to impact in Africa. If a safe orbit has not been attained, the mission controller back at Houston can initiate an abort, causing the spacecraft to splash down in the Atlantic emergency recovery zone just before Africa. In other words we must know where a manned satellite is in real time; we cannot wait for Minitrack interferometer data from several stations to be analyzed. Radar provides the necessary split-second tracking data.

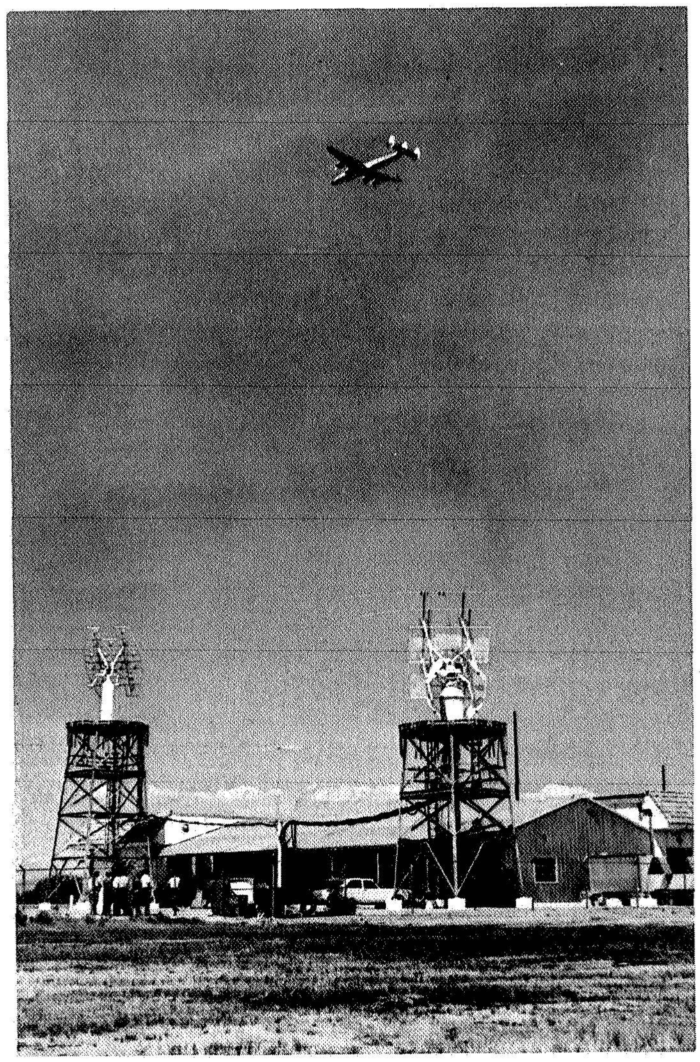
The tracking situation is much the same during reentry and recovery. The mission controller has to know exactly where the spacecraft is in order to fire the retrorockets at exactly the right time. If his timing is off, the spacecraft may land far outside the recovery area—perhaps on land. Rendezvous maneuvers in orbit also require real time tracking data. The MSFN, then, was built around the radar set.

How the MSFN Radars Work

On April 30, 1903, a German engineer named Christian Huelsmeyer received a patent for a "process for reporting distant metallic objects to an observer by means of electric waves." The essence of radar is found in Huelsmeyer's invention—the bouncing of radio waves off objects and listening for the echoes. A great deal more work was done by American and British engineers in the 1920s and 1930s before radar became a household word during World War II. Today, radar is sensitive enough to map the mountains on the Moon and detect a metal object the size of a dinner plate in a 500-mile orbit.

A radar transmitter is like a radio flashlight. Short radio waves—just a few centimeters from crest to crest—are squirted from a waveguide into a metallic

12 *The Guaymas, Mexico, station, showing tracking and data acquisition antennas.*



dish-shaped reflector. The reflector focuses them into a narrow, pencil-like beam similar to the flashlight's beam. A major difference is that radar's microwaves* are emitted in an intense pulse only a few millionths of a second long. During these scant microseconds, the radar may generate a million watts of power, in contrast to the flashlight's steady watt or two.

The pulse of radar waves moves out at the speed of light in search of the target. In a microsecond, it has already traveled 1000 feet; in 1¼ seconds it could reach the Moon. As the pulse travels, however, its intensity decreases according to the inverse square law—the pulse's power is cut to one fourth when the distance from the transmitter is doubled. When the pulse finally hits a target, only a tiny fraction of the radio energy in the pulse bounces back in the direction of the waiting radar antenna. The echo, moreover, also suffers at the hands of the inverse square law. The echo energy finally collected by the radar antenna has been weakened going out and coming back; its strength varies as the inverse fourth power of the target distance. The size, shape, and material of the target also affect echo strength. If the original transmitted pulse was at a power level of one million watts, the echo is often as weak as one micromicrowatt, representing an attenuation of 10^{-18}.

An MSFN radar measures the distance of a satellite by timing the echo. For every 10.7 microseconds delay, the target must be a mile away. A radar receiver thus must have a very fast electronic clock in addition to many stages of amplification.

Target detection and range measurement are only part of radar's stock in trade. From the antenna pointing angle, the radar operator gets target bearing, though not with Minitrack accuracy. Even more important, radar measures target range rate from the Doppler effect. By feeding radar-determined range and range rate into a computer that knows the laws of motion, we can determine the orbit of a satellite or the trajectory of a sounding rocket.

Because satellites are small and far away, it is customary to install a radar transponder on those that are to be tracked by radar. The radar pulse triggers the transponder, causing it to emit a pulse in response—a pulse that is much stronger than the normal echo. The radar antenna measures transponder responses rather than echoes. The strengths of these artificial echoes vary only as the inverse square of the distance, making the satellite easier to track.

Growth of the MSFN

Engineers at NASA's Langley Research Center, at Hampton, Virginia, began work on a worldwide radar, telemetry, and communications network for tracking manned satellites in 1958.

The network that finally evolved consisted of 18 stations stretching from Cape Kennedy southeastward; across Africa, the Indian Ocean, Australia; thence to Hawaii and the West Coast of the U.S.; across the continent to the Atlantic recovery zone. There were 16 land sites and two instrumented ships in a belt that lay beneath the three orbits originally planned for the most ambitious shots in the Mercury Program. All of the stations were linked by a terrestrial communication network to the Mission Control Center, at Cape Kennedy, and the computers at Goddard Space Flight Center, Greenbelt, Maryland. The Mercury Network became operational on July 1, 1961. It performed with high reliability during the entire Mercury Program.

When NASA's Gemini Program came along in 1963 with its two-man spacecraft and plans for rendezvous in space, the Mercury Network had to be modified in several ways. Because of the presence of two spacecraft in orbit during rendezvous maneuvers, the ground stations had to add extra antennas and more radio equipment to communicate with both sets of astronauts. The Mercury radars, however, were not changed because they could track both spacecraft by switching rapidly from one to the other. Some of the Gemini

**Radar's microwaves are electromagnetic waves with wavelengths between roughly 3 mm and 30 cm. Visible light is also electromagnetic in nature, but the wavelengths are much shorter—400 to 700 millimicrons (4 to 7 x 10^{-7} meters).*

missions lasted as long as two weeks and the spacecraft traveled over a larger portion of the globe than any Mercury shot. Supplementary stations, including instrumented ships, were temporarily added to the Mercury Network for Gemini. Finally, there was a trend to consolidate tracking and communications into fewer, but better-instrumented sites. Overall, the changes for Gemini were minor. But it was during the Gemini Program (1963 to 1966) that the Mercury Network became the Manned Space Flight Network.

The Apollo Program, though, was a different matter; extensive changes in the network were required. When Apollo spacecraft leave the Earth far behind on their way to the Moon, they go beyond the range of conventional radars. The technical challenges and responses in planning the network are best summarized in a table:

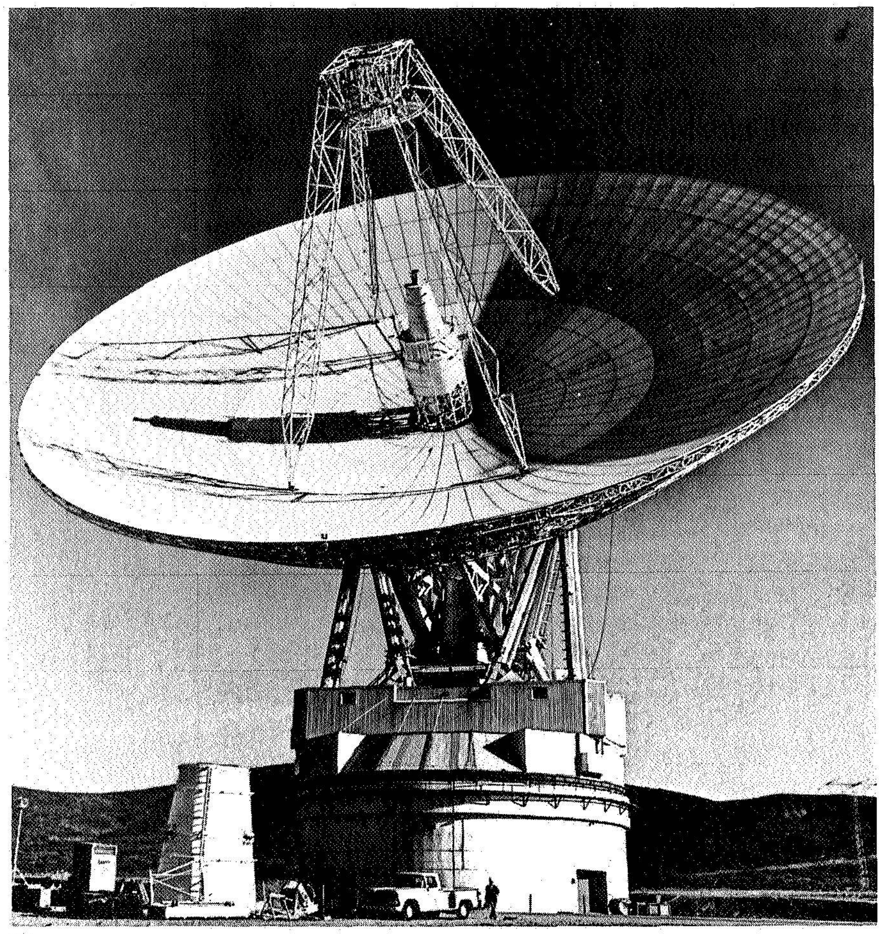
New Apollo Requirement	MSFN Response
Range and range rate data essential for Moon trip	Adoption of Unified S-Band tracking approach (see USB, below)
Tracking and communication at lunar distances impossible for old MSFN equipment	Installation of three 85-foot-diameter paraboloidal antennas at DSN sites
Tracking and communication near Earth	Installation of 30-foot paraboloidal antennas at eleven MSFN sites
Expanded geographic coverage required to track and communicate with the spacecraft during and immediately following injection into the lunar flight path and for the reentry.	Addition of five ships, eight aircraft, a transportable station, many secondary sites, and communication satellites

The result of all these changes is that the old Mercury Network core is hardly discernible today. The most important new feature is the Unified S-Band approach.

Unified S-Band (USB)

USB stands for Unified S-Band. The adjective unified refers to the fact that, for the Apollo lunar mission, NASA has consolidated all of the tracking and communication functions (voice, telemetry, commands) into a single electronic framework, a single radio telecommunication link. Instead of independent, separate sets of equipment in the spacecraft and at each site for each of these functions, NASA has integrated everything into one set of hardware. The remainder of the system name comes from the adoption of frequencies in the so-called S-Band (1000 to 5000 MHz).

Intrinsic to USB is a tracking technique long employed by NASA's Deep Space Network (DSN) in tracking lunar, planetary, and deep space probes. The problems involved in tracking these distant spacecraft are essentially the same as those encountered with satellites in highly eccentric orbits—range and range rate data are essential where angular bearings change but little. In designing the USB, the approach to obtaining range and range rate was rather similar to that used in sidetone ranging. Instead of making phase measurements, however, the time of signal transit (round trip) is measured to obtain spacecraft range.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The Deep Space Network (DSN)

Neither the early MSFN radars nor the STADAN radio interferometers are of much help in tracking probes that leave the Earth far behind. A completely different system was developed by the Jet Propulsion Laboratory for tracking far-ranging probes through the solar system. Later, the MSFN adopted some of the JPL techniques in its system, and STADAN incorporated a range and range rate tracking system similar in some respects to the JPL approach.

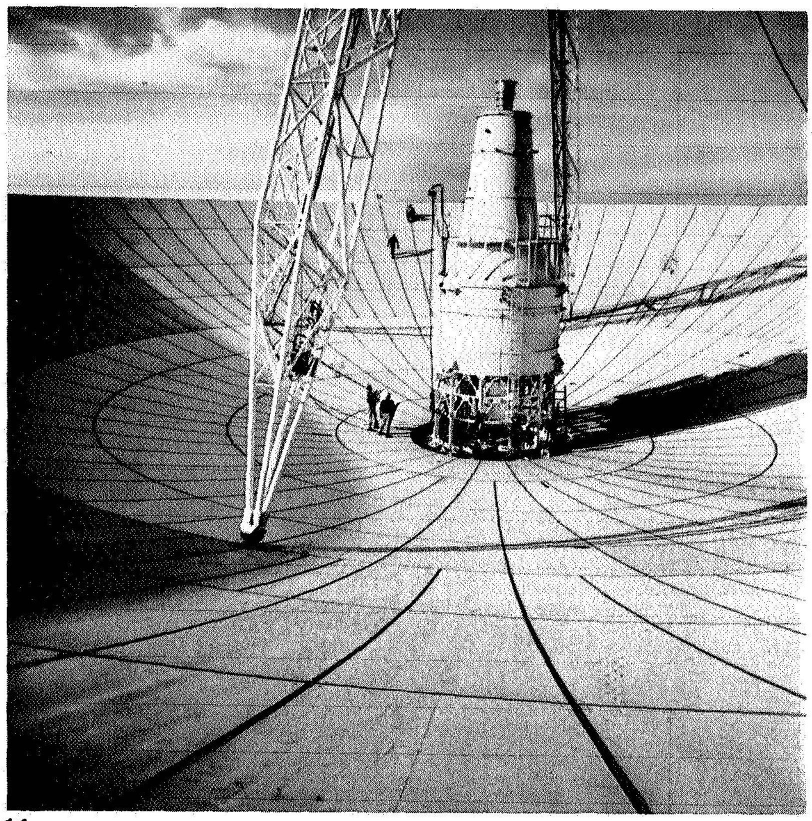
When the Jet Propulsion Laboratory programs were assimilated by NASA in December of 1958, JPL had already conceived the essentials of what was to become the Deep Space Network or DSN. The primary element in the tracking system was a large paraboloidal antenna with a narrow reception pattern. Angular bearings of distant spacecraft were found by centering them in this reception pattern and noting the antenna pointing angles. The spacecraft, of course, had to make itself visible through radio signals from its transponder. Range rate data were obtained from the Doppler effect. Finally, by triggering a transponder on the spacecraft and timing the round trip signal transmissions, range information resulted. Taken together, these data were sufficient for accurate trajectories.

NASA launched its first series of five Pioneer space probes in the general direction of the Moon between 1958 and 1960. They were the first U.S. spacecraft to be tracked by the embryonic DSN. During this period, the DSN did not have worldwide coverage. For example, for the flights of Pioneers III and IV, the DSN consisted of an 85-foot-diameter paraboloid at Goldstone, California, a 10-foot-diameter dish in Puerto Rico, and a still smaller antenna at the Florida launch site. The Jodrell Bank 250-foot radio astronomy antenna in England, and a 60-foot antenna at South Point, Hawaii (under Air Force operation) cooperated during the Pioneer Program by tracking the spacecraft when they moved out of the view of DSN stations.

How many stations are really needed to keep a spacecraft far out in space within view of at least one station? Two stations 180° apart are not sufficient because they would not provide sufficient overlapping of coverage of a deep space probe as the Earth rotates

13 The Goldstone 210-foot paraboloid used for tracking probes far out in space.

14 Workmen standing in the reflector of the Goldstone 210-foot antenna.



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and the spacecraft passes from the view of one antenna into that of the other. Three stations spaced approximately equidistant around the Earth do the job well. The DSN was planned with this fact in mind.

By the time the first Ranger probes were launched toward the Moon in 1961, 85-foot dishes had been installed at Woomera, Australia, and Johannesburg, South Africa. With the Goldstone station, the trio was complete. During the early 1960s, the network was called the Deep Space Instrumentation Facility (DSIF). The DSIF tracked the first Venus probe, Mariner II, to a distance of 60 million miles in 1962.

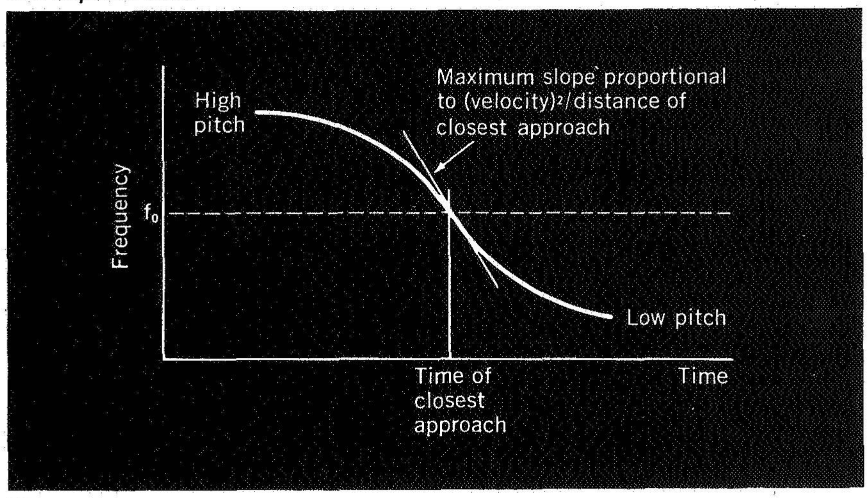
In 1965, the network (now called the DSN) guided Mariner IV to within 6200 miles of Mars. Mariner IV was some 135 million miles from Earth at the time of planetary encounter. After Mariner IV went into orbit around the Sun and became an artificial planet, the DSN tracked and communicated with the spacecraft at distances well over 200 million miles.

A major addition to the DSN in recent years has been a 210-foot paraboloidal antenna near the 85-foot dish at the Goldstone station. Antenna size is important in deep space work for two reasons: (1) the larger the antenna the more accurate the pointing data; and (2) the bigger the antenna aperture, the farther it can track a space probe, the more data it can receive from it per unit time, and the better it can control the space probe. With its 210-foot antenna, the DSN can work probes more than 200 million miles away and measure their ranges to within 45 feet and their range rates to within 1 millimeter per second.

In addition to the Goldstone 210-foot dish, NASA has added several more 85-foot paraboloids to the DSN to improve geographical coverage and support the Apollo Program. At Madrid, there are two DSN 85-footers and one belonging to the MSFN. Goldstone now has one MSFN plus three DSN 85-foot dishes. Finally, a DSN dish has been installed at Canberra alongside the 85-foot MSFN paraboloid. This redundancy increases astronaut safety during Apollo; if an MSFN paraboloid should go out of commission, a DSN dish will be ready to take over.

15 *The Doppler record of a passing satellite permits computation of the orbit from the slope of the curve.*

16 *Schematic of the laser tracking experiments performed with Explorer XXII.*



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Some Other Tracking Schemes

Harnessing the Doppler Effect

NASA uses the Doppler effect to compute range rate in radars, in sidetone approach, and in tracking deep space probes with the DSN. There is, however, a way to obtain all the data necessary for orbit computation by just listening (with radio ears, of course) to the beacon signal from a passing satellite.

A satellite approaching a ground station with a beacon emitting 136-MHz signals will appear to a ground station to be emitting signals a few kilohertz higher than it really is because of the Doppler effect. The signals will be correspondingly lower when the satellite recedes toward the opposite horizon. At one point in its transit across the sky, the satellite will appear to be emitting exactly the frequency it actually does emit; that is, the Doppler effect disappears. This occurs when the satellite is at the point of closest approach and is moving neither toward nor away from the ground station. In the train analogy, this is the instant when the train engine passes the observer.

If the apparent satellite signal is carefully plotted against time, a smooth curve connects the high-pitch and low-pitch plateaus. The shape of this curve is full of information that can be extracted by a mathematician. The speed of the satellite and the distance of closest approach can be obtained. In fact, enough information can be garnered from the Doppler record of one satellite pass to compute the complete orbit.

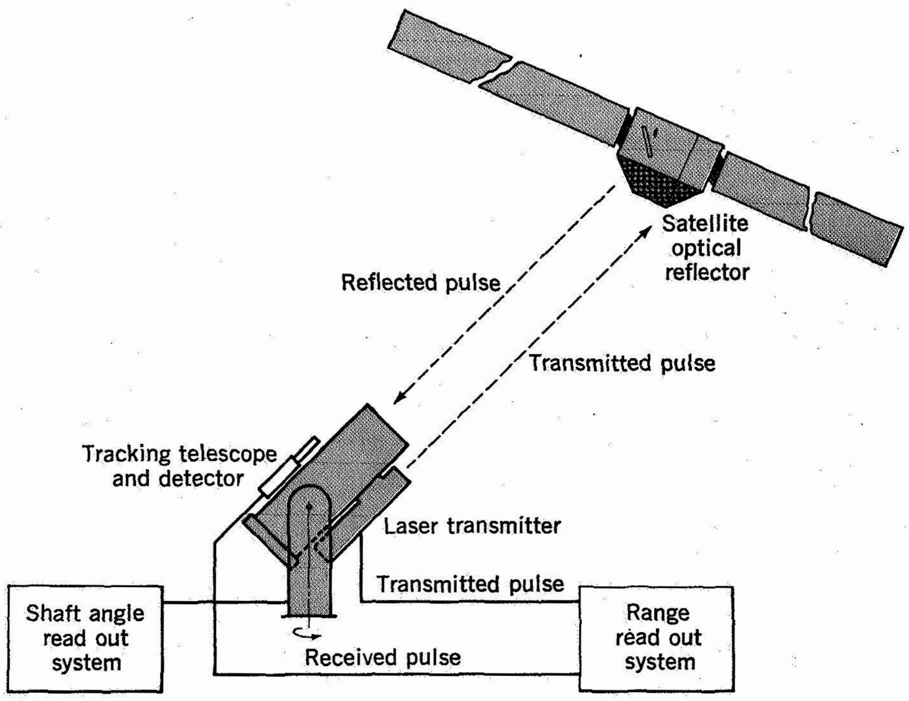
Doppler tracking is employed by the U.S. Navy in its navigation satellite program. Scientists also employ Doppler tracking to measure small changes in satellite orbits caused by variations in the upper atmosphere and the Earth's gravitational field. For example, variations in the density of the Earth below a satellite can cause its orbit to dip or rise a few hundred feet. Doppler tracking thus helps gain insight into the structure of the Earth's crust.

Laser Illumination of Satellites

In 1955 and 1956, when engineers were first studying the satellite tracking problem, powerful searchlights were considered for illuminating the satellite so it could be easily seen by ground stations. Searchlights were dropped in favor of radio interferometers; but the recent development of high power lasers reopened the question of artificial satellite illumination.

Lasers generate highly concentrated pulses of light energy—so powerful that they may be used to weld metals. Laser light is also nearly monochromatic; that is, almost all of one wavelength, like a radar pulse. Laser tracking, then, would be similar to radar tracking: a laser would be aimed at a satellite and the reflected light would be detected and analyzed like radar's radio echo.

Laser tracking has proven successful in a limited way



with several satellites, especially Explorers XXII and XXVII. Both of these satellites were outfitted with arrays of quartz corner reflectors—little quartz cubes cut in such a way as to reflect laser light straight back at the laser ground station with high efficiency. In practice, the laser beam is so narrow and pencil-like that the location of the satellite has to be known accurately before a direct hit can be made. This has limited the use of lasers in tracking to special experiments in geodesy, in which scientists attempt to locate points on the Earth more accurately with respect to one another.

Traffic Jam In the Sky

The big NASA tracking networks are supported by military and foreign tracking networks. With dozens of radars, cameras, and interferometers scanning the heavens the world over, satellites do not get lost any more, as Explorer X did for a while in 1961. In ten years the tracking problem has changed from trying to find a lone satellite in an empty sky to trying to keep track of over a thousand pieces of hardware in orbit around the Earth, around the Moon, and cruising far out in deep space around the Sun. Instead of the Moonwatch teams and a few lonely, isolated Minitrack stations, we have now "wired the world," as one NASA tracking expert has put it. NASA can communicate with any of its active satellites and space probes at the flick of a switch—even if the spacecraft is on the Moon, flying by Mars, or taking pictures of the weather around Australia.

RECAPITULATION OF TRACKING TECHNIQUES

How We "See" Spacecraft	Tracking Technique	Examples of Use
Solar illumination	Optical tracking	Moonwatch, Baker-Nunn cameras, theodolites
Artificial illumination	Radars, lasers	Sounding rocket and launch ranges, the MSFN
Through beacons or transponders on spacecraft	Radio interferometers	STADAN (Minitrack) and various launch range tracking systems
	Sidetone tracking	USB, STADAN range and range rate system
	Doppler effect	Intrinsic in radars, sidetone, and DSN tracking
	Big radio dishes	DSN

Additional Reading

For titles of books and teaching aids related to the subjects discussed in this booklet, see NASA's educational publication EP-48, Aerospace Bibliography, Fourth Edition.

Information concerning other educational publications of the National Aeronautics and Space Administration may be obtained from the Educational Programs Division, Code FE, Office of Public Affairs, NASA, Washington, D. C., 20546.

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EP-55

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Spacecraft Tracking

National Aeronautics and Space Administration